

Collider Signatures of Heavy Quarks

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arXiv:0706.xxxx - *AA, Marcela Carena, Tao Han, Jose Santiago*

arXiv:0706.xxxx - *Kaustubh Agashe, AA, Tao Han*

Outline

- Introduction of heavy quarks
- Motivation
- Signal and Background
- Current constraints
- Future analysis
- Conclusion

What we study

- Generic heavy quarks with arbitrary couplings
LH only, RH only and both

$$\mathcal{L} \propto k_\ell \frac{g}{2\sqrt{2}} (1 - \gamma_5) + k_r \frac{g}{2\sqrt{2}} (1 + \gamma_5)$$

- D_i : charge -1/3 heavy quarks that mix with SM quark of i^{th} generation
- U_i : charge 2/3 heavy quarks that mix with SM quark of i^{th} generation
- Study both CC and NC processes for Tevatron and LHC
- Preliminary studies presented here for CC interactions of D_1 (with LH couplings only) at the Tevatron

Heavy Quarks in New Physics

Warped extra dimensions

- Extend bulk gauge symmetry to custodially symmetric

$$SU(2)_L \times SU(2)_R$$

Agashe, Delgado, May, Sundrum

- KK excitations of gauge bosons \sim few TeV
- $SU(2)_R$ symmetric partners of RH quarks are light
- Custodial symmetry plus L - R symmetry protect b coupling

- Bidoublets

Agashe, Contino, Da Rold, Pomarol

- Higgs propagating in bulk - Gauge Higgs Unification model
 - Based on $SO(5) \times U(1)_X$ to $SU(2)_L \times SU(2)_R \times U(1)_X$ on IR brane and $SU(2)_L \times U(1)_Y$ on UV brane

Carena, Ponton, Santiago, Wagner

- Warped GUTs

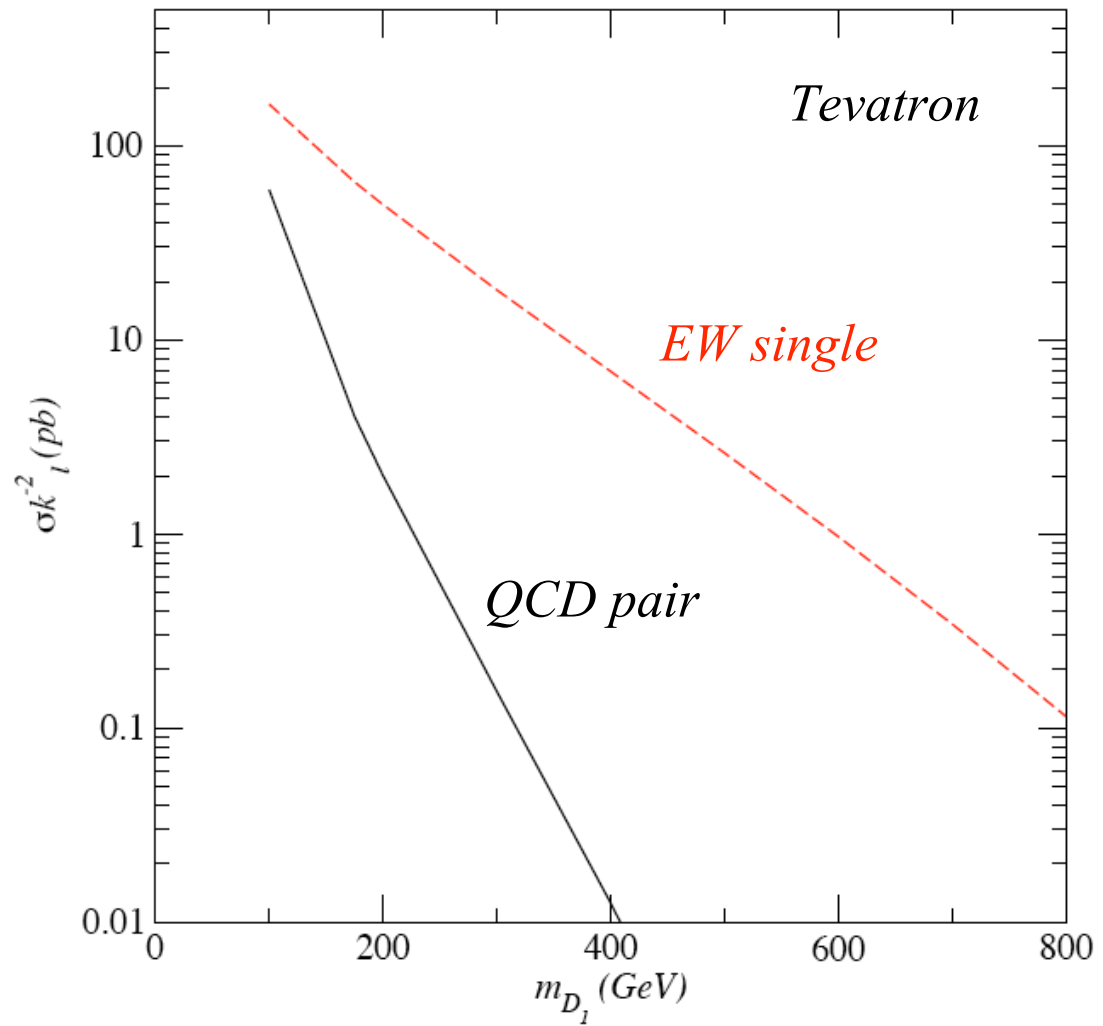
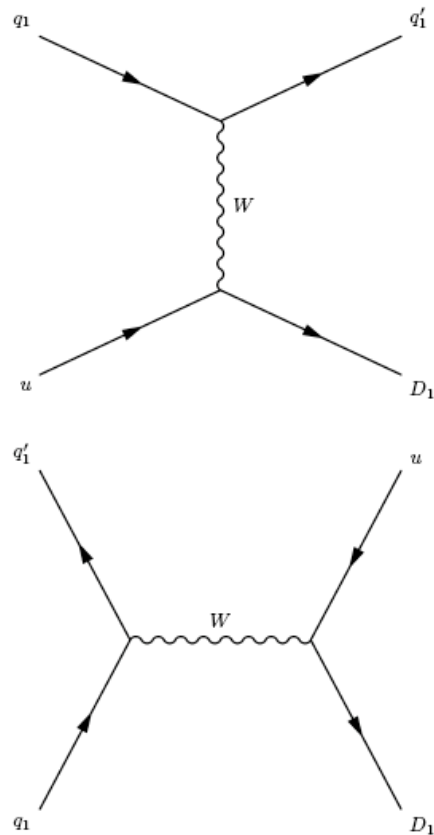
Agashe, Servant

- etc.

We study generic heavy quarks!

Signal Process: Production

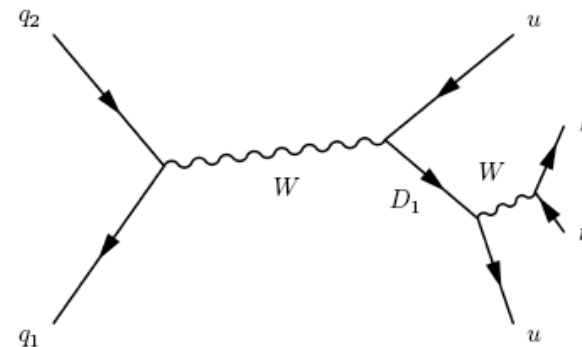
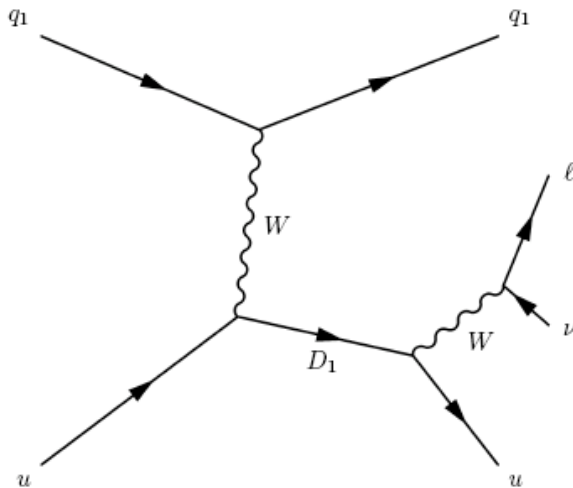
QCD pair production vs Electroweak single production



Signal Process: Decay

$$pp / p\bar{p} \rightarrow qD_1 \rightarrow quW \rightarrow qu\ell\nu$$

$$\ell = \mu \text{ only}$$



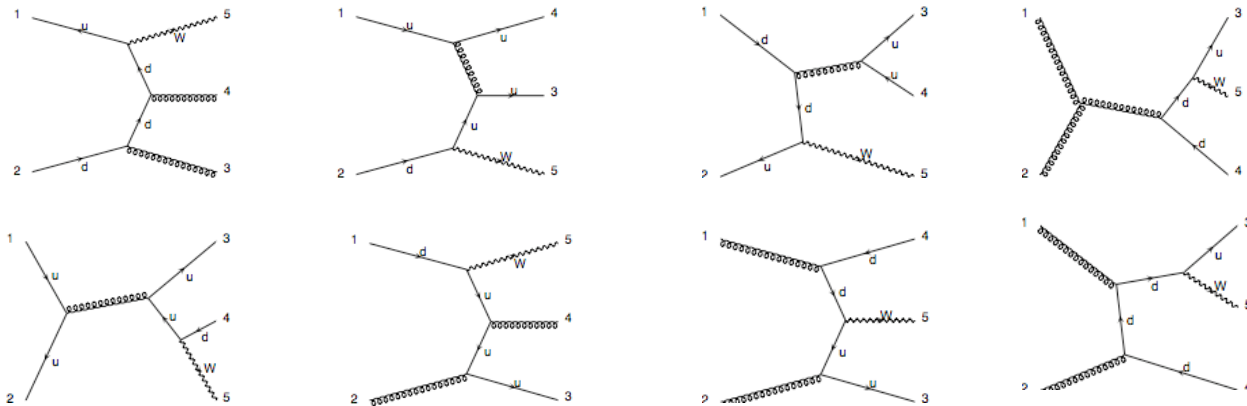
- Both D_1 and \bar{D}_1 considered
- Full spin correlation maintained
- Tevatron, $E_{cm} = 1.96$ TeV

Signal: $2j + \mu + \cancel{E}_T$

Background Processes

Main Background:

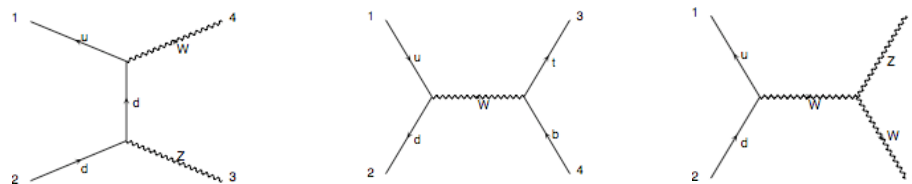
QCD processes $p\bar{p} \rightarrow 2j + W^\pm \rightarrow 2j + \ell^\pm + \nu$



Other Background:

EW processes $p\bar{p} \rightarrow Z + W^\pm \rightarrow 2j + \ell^\pm + \nu$

Single top $p\bar{p} \rightarrow t + b \rightarrow W^\pm bb \rightarrow 2j + \ell^\pm + \nu$



Cuts

Basic Cuts:

$$\begin{array}{lll} p_T(jet) > 15 \text{ GeV} & |\eta_{jet}| < 3 & \Delta R_{jj} > 0.7 \\ p_T(lep) > 15 \text{ GeV} & |\eta_{lep}| < 2 & \Delta R_{j\ell} > 0.5 \\ p_T(miss) > 15 \text{ GeV} & & \end{array}$$

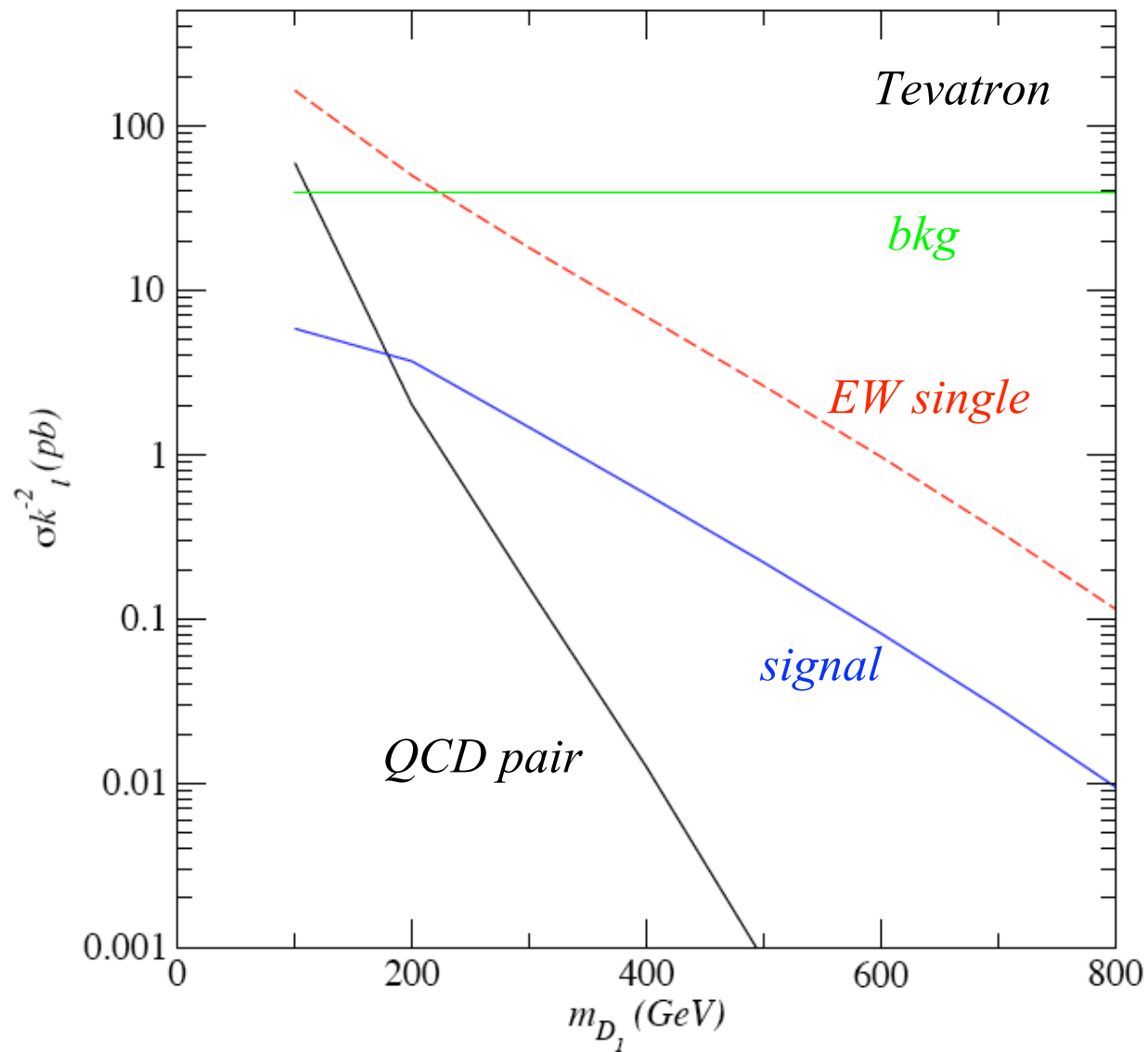
Smearing:

Energy resolution parameterized by: $\frac{\Delta E}{E} = \frac{a}{\sqrt{E}} \oplus b$

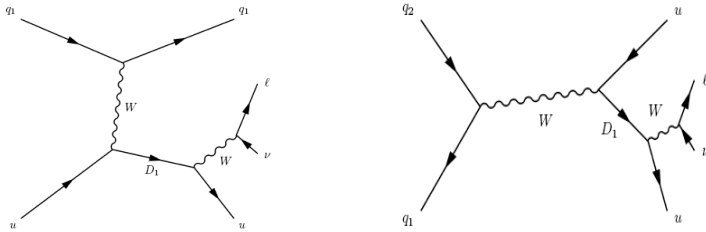
$$\text{ECAL:} \quad a = 13.5\% \quad b = 1.5\%$$

$$\text{HCAL:} \quad a = 75\% \quad b = 3\%$$

Signal vs Background



Signal vs Background Distributions

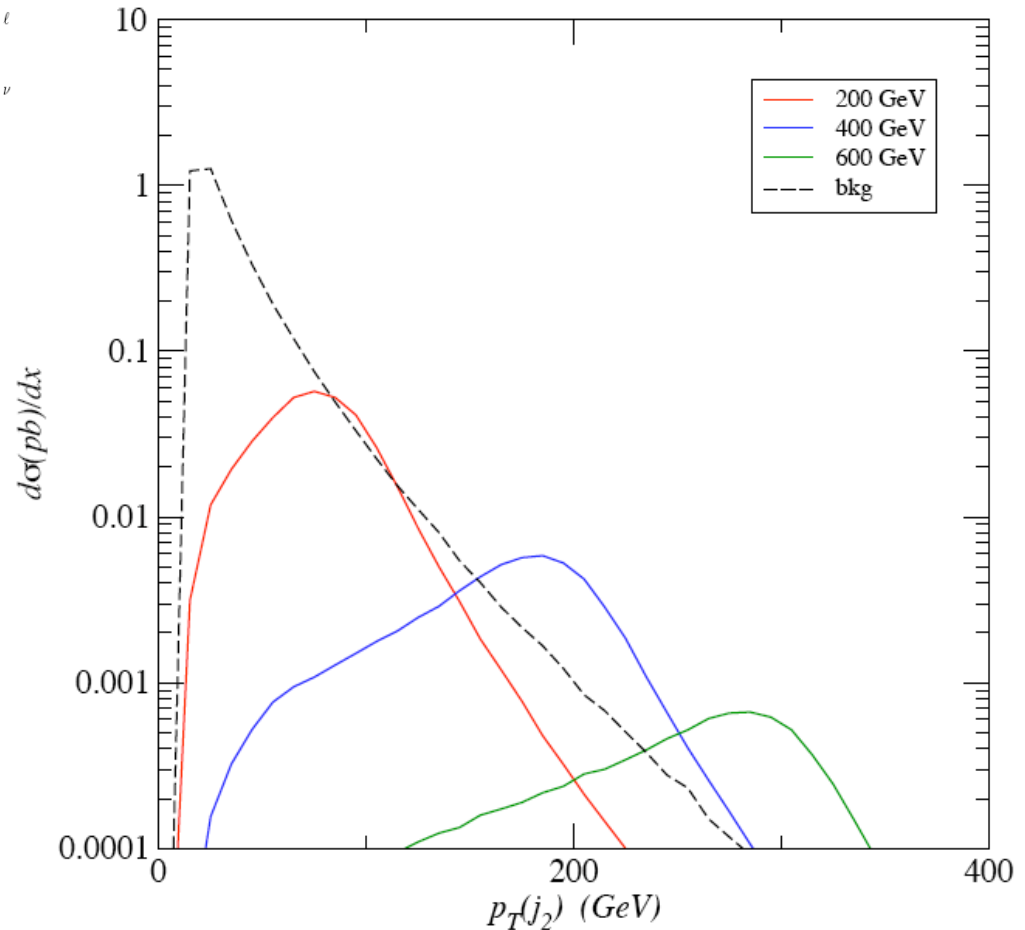


Improved Cuts:1

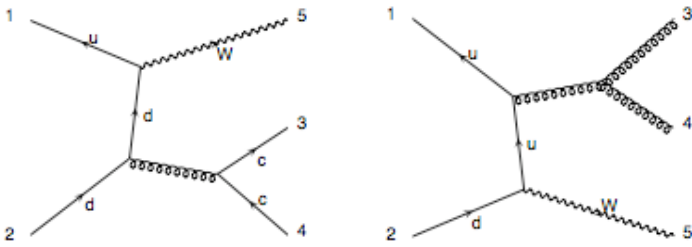
$$p_T(j_2) > \frac{m_{D_1}}{4}$$

Signal efficiency:
 $\sim 83 \text{ to } 90\%$

Background efficiency:
 $\sim 0.1 \text{ to } 14\%$



Signal vs Background Distributions



Improved Cuts: 2

$$\Delta R_{jj} > 1.5$$

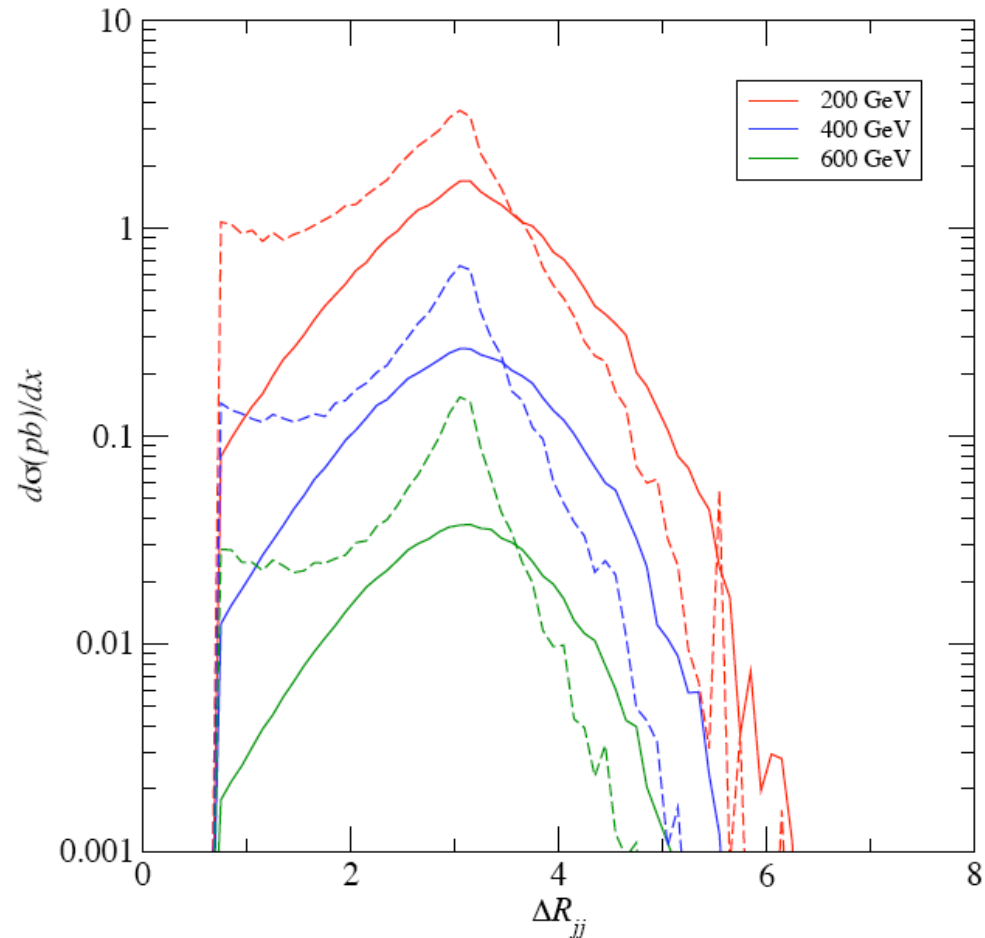
$$\Delta R_{j\ell} > 0.8$$

Signal efficiency:

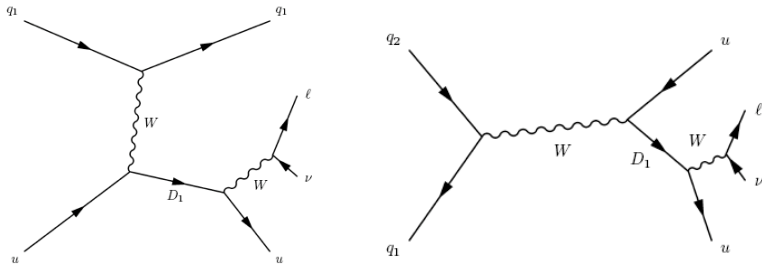
~ 93 to 95%

Background efficiency:

~ 68 to 80%



Signal vs Background Distributions



Improved Cuts: 3

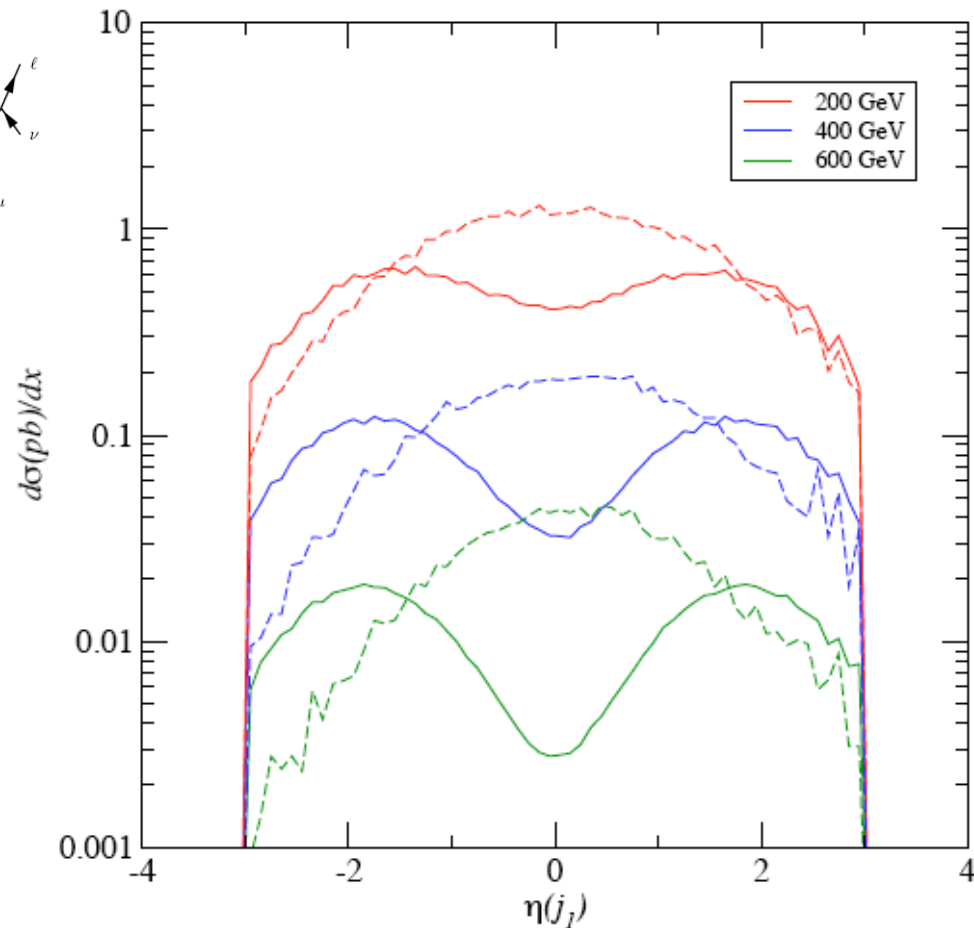
$$0.5 < |\eta(j_1)| < 3.0$$

Signal efficiency:

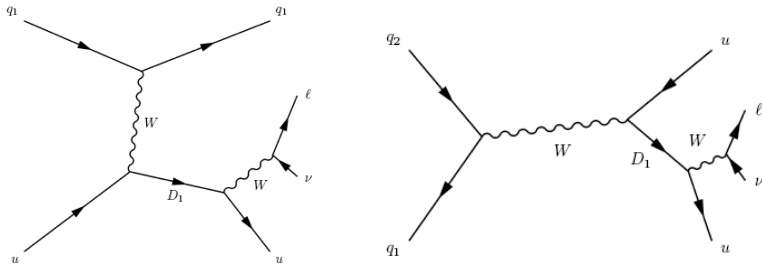
~ 85 to 96%

Background efficiency:

~ 64 to 72%



Signal vs Background Distributions



Improved Cuts: 4

$$m_{D_1} - \frac{1}{4}m_{D_1} < m_T(j_2W)$$

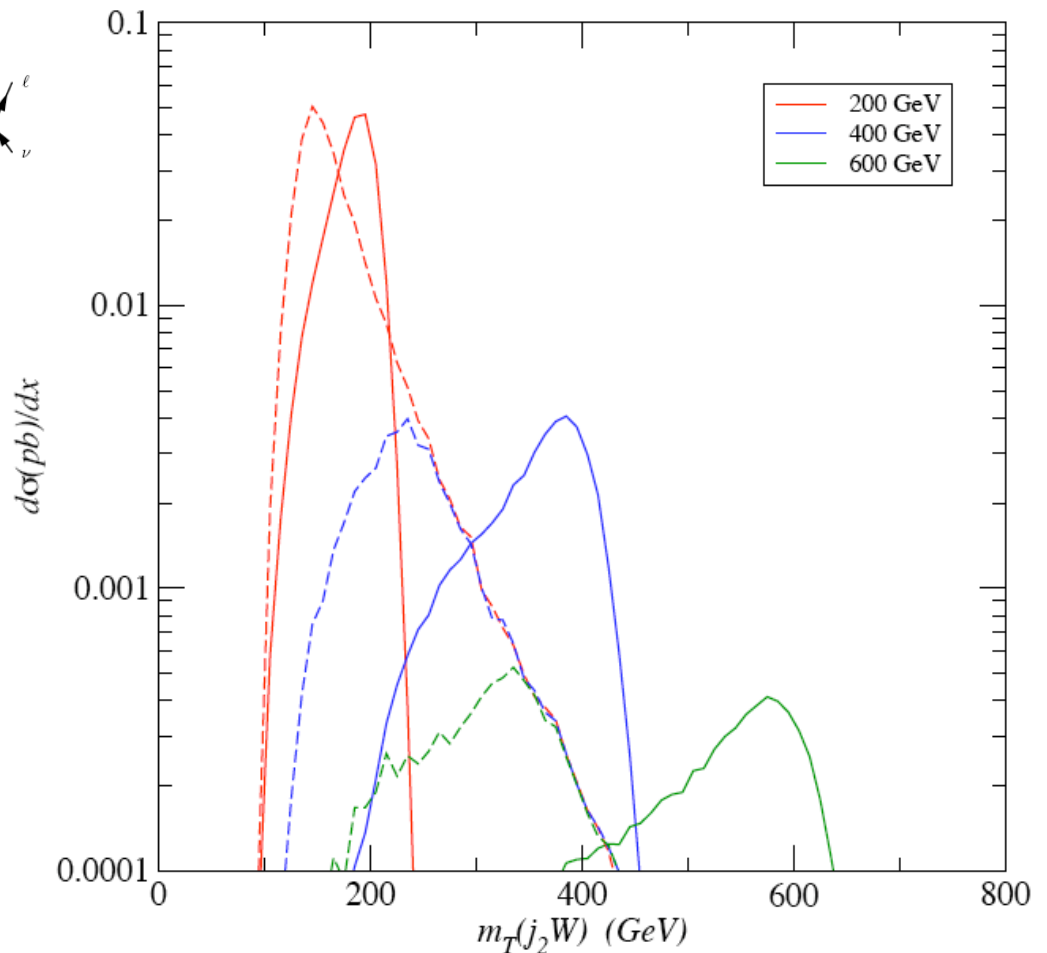
$$m_{D_1} + \frac{1}{4}m_{D_1} > m_T(j_2W)$$

Signal efficiency:

~ 78 to 97%

Background efficiency:

~ 3 to 56%



$$m_T^2(j_2W) = [p_T^{j_2} + \sqrt{m_W^2 + (\vec{p}_T^W)^2}]^2 - (\vec{p}_T^{j_2} + \vec{p}_T^W)^2$$

Improved Cuts

$$p_T(j_2) > \frac{m_{D_1}}{4}$$

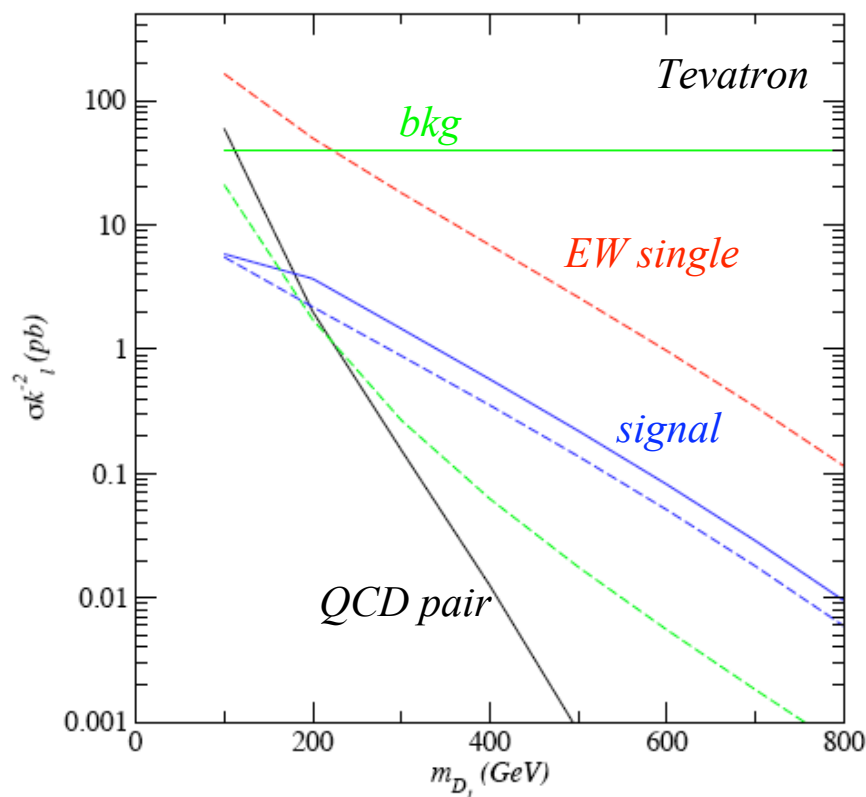
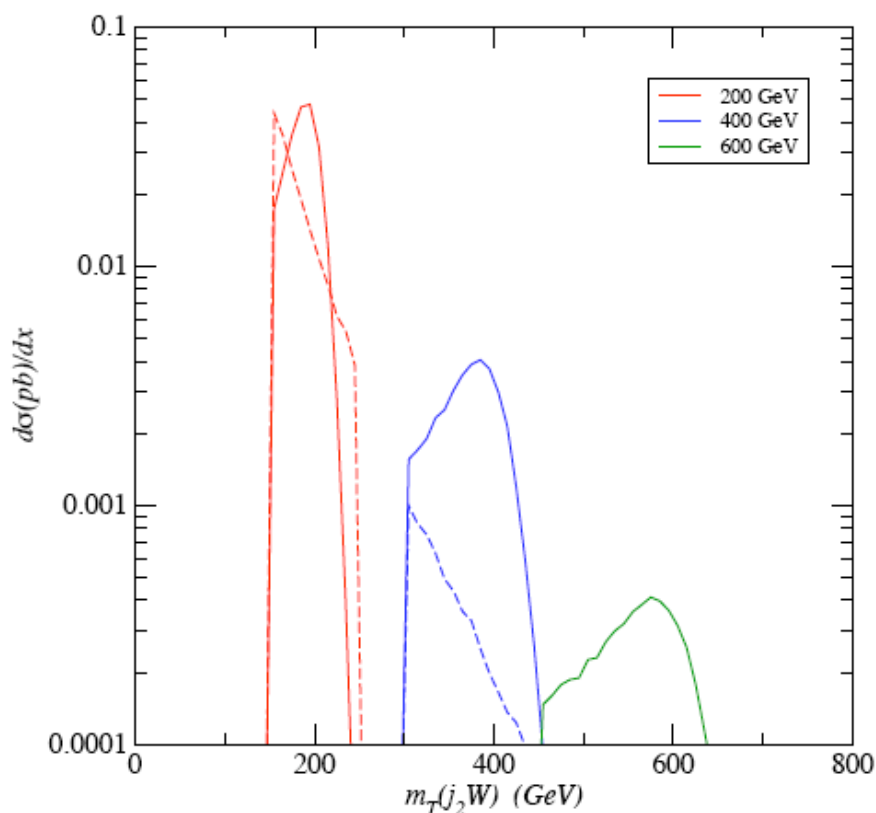
$$0.5 < |\eta(j_1)| < 3.0$$

$$\Delta R_{jj} > 1.5$$

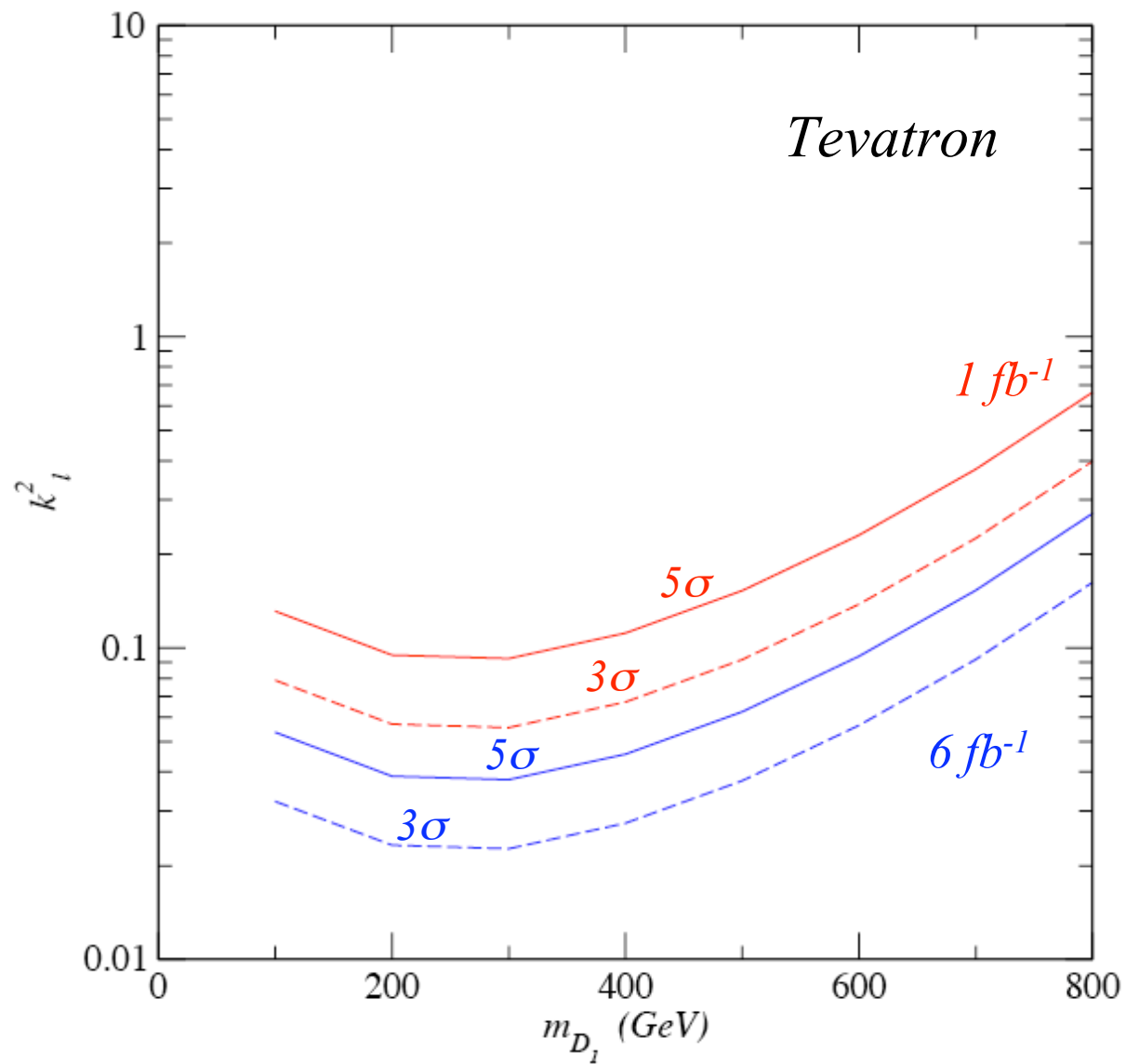
$$\Delta R_{j\ell} > 0.8$$

$$m_{D_1} - \frac{1}{4}m_{D_1} < m_T(j_2 W)$$

$$m_{D_1} + \frac{1}{4}m_{D_1} > m_T(j_2 W)$$



Sensitivity at Tevatron



Current Constraints

- Searches for fourth generation
 - Limits on b' are around 300 GeV from 1 fb^{-1} data
 - Limits are from $b' \rightarrow b Z$ mode
 - No $b' \rightarrow Wj$ mode analysis available
- Searches for $W^\pm H(\text{or } X) \rightarrow l \nu 2j$
 - Limits on $\sigma.BR(H(\text{or } X) \rightarrow bb)$
 - Translate limits to our case $\Rightarrow m_{D_1} > 100\text{ GeV}$
- Limits from on a t' ($\rightarrow Wb$) are 265 GeV with about 1 fb^{-1}
 - Applicable for third generation(b), results here for D_1

<http://www-cdf.fnal.gov/physics/exotic/exotic.html>

<http://www-cdf.fnal.gov/physics/new/top/top.html>

Further analysis in progress

- Consider RH couplings and generic LH + RH scenarios
- Electron as well as muon channel
- Heavy quarks that mix with second and third generations
- Study sensitivity at the LHC
- NC process - $2j + l^+ l^-$ channel.

Better efficiency - two leptons

Better reconstruction - no missing energy

Conclusions

- Considered single production of heavy quarks with arbitrary coupling
- Single production has enhanced sensitivity compared to QCD pair production
- Can probe heavy quark mass up to 800 GeV at the Tevatron
- Heavy quarks can be found in many new physics scenarios

Example: Light Kaluza-Klein quarks in Randall-Sundrum models with custodial symmetry

We can still discover new physics at the Tevatron!

Supplementary Slides

Improved Cuts

$$p_T(j_2) > \frac{m_{D_1}}{4}$$

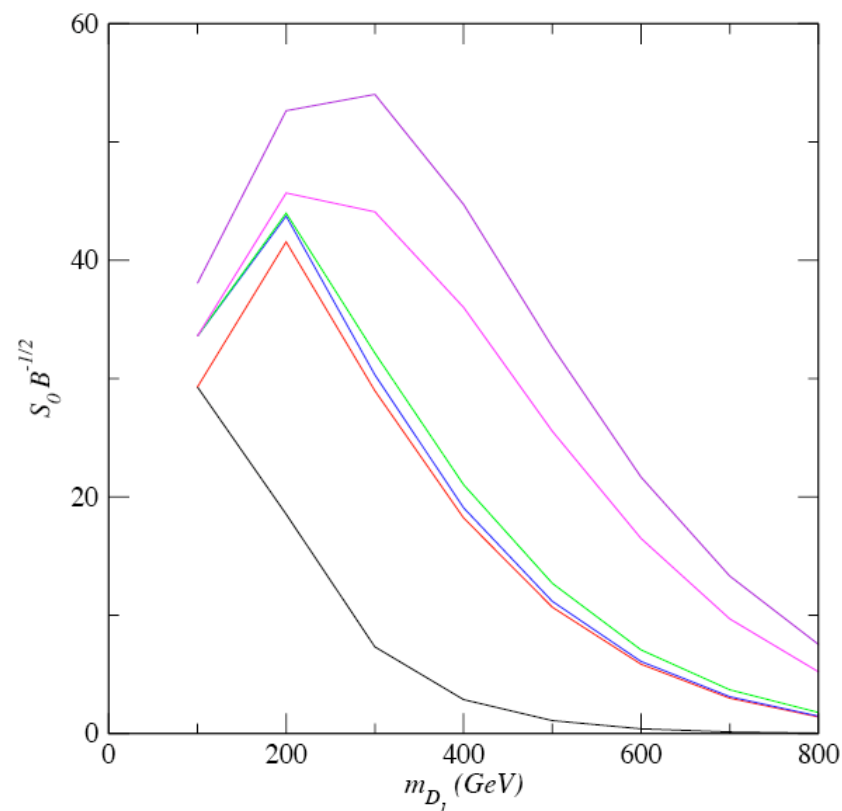
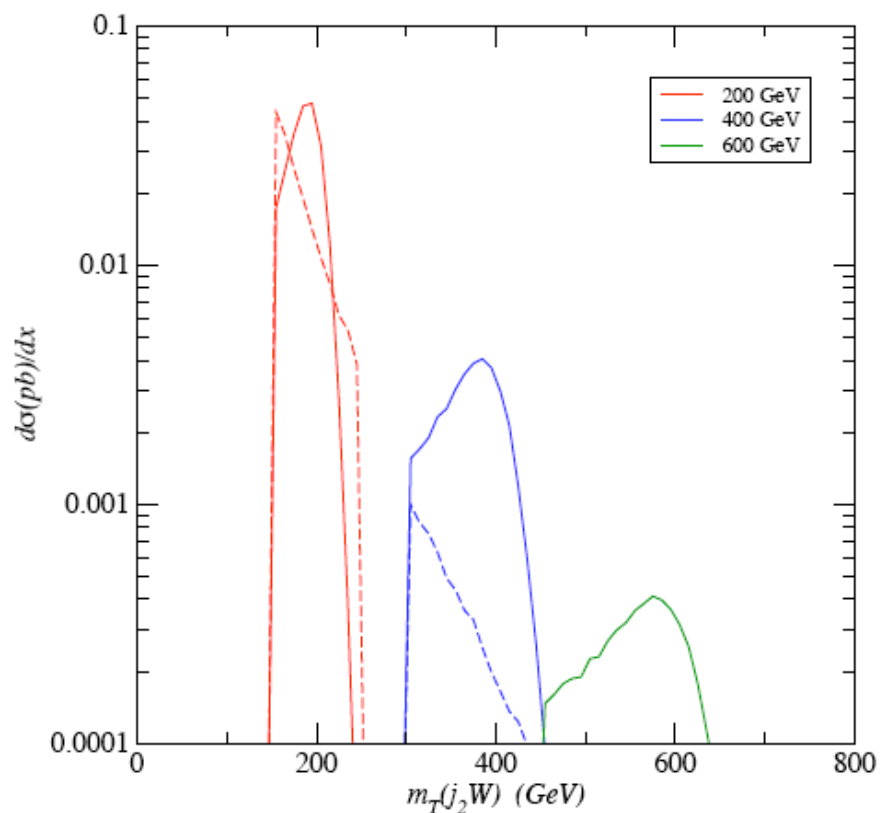
$$\Delta R_{jj} > 1.5$$

$$m_{D_1} - \frac{1}{4}m_{D_1} < m_T(j_2 W)$$

$$0.5 < |\eta(j_1)| < 3.0$$

$$\Delta R_{j\ell} > 0.8$$

$$m_{D_1} + \frac{1}{4}m_{D_1} > m_T(j_2 W)$$



Example: warped extra dimension

- Warped extra dimension models address gauge hierarchy problem
- Background geometry a slice of AdS space with curvature scale k
- Due to AdS warping exponential hierarchy between mass scales at two ends of extra dimension generated
- Original set up all SM fields are localized on IR brane
- Leads to large FCNC and proton decay
- SM fields propagate in the bulk and Higgs localized on IR brane - attractive mechanism for Yukawa structure and prevents excessive FCNCs.
- Constraints from precision electroweak data

Heavy Quarks in New Physics

- Extend bulk gauge symmetry to a custodially symmetric $SU(2)_L \times SU(2)_R$
- Reduces tree level contribution to T parameter
- Gauge bosons with masses $\sim 3 \text{ TeV}$
- RH quarks included in doublets under $SU(2)_R$ symmetry
- $SU(2)_R$ symmetric partners can be very light (RH top)
- This mode mixes with bottom quark and induces corrections to Zbb coupling
- Strong constraints on these models

Agashe, Delgado, May, Sundrum

Heavy Quarks in New Physics

- *Gauge-Higgs Unification* - Higgs field is a pNGB that arises as component along extra dimensions of gauge fields of broken symmetries
- Higgs field corresponds to zero mode of A_5 gauge boson along the broken direction of $SO(5)/O(4)$
- $SO(4) \times U(1)_X$ broken to $SU(2)_L \times SU(2)_R \times U(1)_X$ on *IR* brane and $SU(2)_L \times U(1)_Y$ on *UV* brane.
- Light higgs and light fermions predicted

*Carena, Ponton,
Santiago, Wagner*

$$\begin{aligned}\xi_{1L}^i &\sim Q_{1L}^i = \begin{pmatrix} \chi_{1L}^{u_i}(-,+) & q_L^{u_i}(+,+) \\ \chi_{1L}^{d_i}(-,+) & q_L^{d_i}(+,+) \end{pmatrix} \oplus u_L^i(-,+), \\ \xi_{2R}^i &\sim Q_{2R}^i = \begin{pmatrix} \chi_{2R}^{u_i}(+,-) & q_R^{u_i}(+,-) \\ \chi_{2R}^{d_i}(+,-) & q_R^{d_i}(+,-) \end{pmatrix} \oplus u_R^i(+,+), \\ \xi_{3R}^i &\sim T_{1R}^i = \begin{pmatrix} \psi_R^i(-,+) \\ U_R^i(-,+) \\ D_R^i(-,+) \end{pmatrix} \oplus T_{2R}^i = \begin{pmatrix} \psi_R^i(-,+) \\ U_R^i(-,+) \\ D_R^i(+,+) \end{pmatrix} \oplus Q_{3R}^i = \begin{pmatrix} \chi_{3R}^{u_i}(-,+) & q_R^{u_i}(-,+) \\ \chi_{3R}^{d_i}(-,+) & q_R^{d_i}(-,+) \end{pmatrix}\end{aligned}$$

Q_i bidoublet under $SU(2)_L \times SU(2)_R$
 $SU(2)_L$ vertically,
 $SU(2)_R$ horizontally
 T_1 and T_2 transform as (3,1) and (1,3) under $SU(2)_L \times SU(2)_R$
 u_i and u' singlets
 $i=1,2,3$ generations

Heavy Quarks in New Physics

- 16 of $SO(10)$ with extra states assigned $(-+)$ BC
- One 16 of $SO(10)$ for each SM: Q_L $-(u_L, d_L)$, u_R, d_R , $L_L = (e_L, \nu_L)$, e_R, ν_R
- One component of $SU(2)_R$ has zero mode other do not - split $SU(2)_R$ components. Similarly for leptons.

$$\begin{aligned}
 \mathbf{16}_{uR} &= \begin{pmatrix} u_R \\ \tilde{d}_R \\ e'_R \\ \nu'_R \\ L'_L \\ Q'_L \end{pmatrix}, \mathbf{16}_{dR} = \begin{pmatrix} \tilde{u}_R \\ d_R \\ e'_R \\ \nu'_R \\ L'_L \\ Q'_L \end{pmatrix}, \mathbf{16}_{eR} = \begin{pmatrix} u'_R \\ d'_R \\ e_R \\ \tilde{\nu}_R \\ L'_L \\ Q'_L \end{pmatrix}, \mathbf{16}_{\nu R} = \begin{pmatrix} u'_R \\ d'_R \\ \tilde{e}_R \\ \nu_R \\ L'_L \\ Q'_L \end{pmatrix}, \mathbf{16}_{QL} = \begin{pmatrix} Q_L \\ L'_L \\ u'_R \\ d'_R \\ e'_R \\ \nu'_R \end{pmatrix}, \mathbf{16}_{LL} = \begin{pmatrix} Q'_L \\ L_L \\ u'_R \\ d'_R \\ e'_R \\ \nu'_R \end{pmatrix}
 \end{aligned}$$

Agashe, Servant

Heavy Quarks in New Physics

- Custodial symmetry with discrete L - R symmetry can protect Zbb coupling
- Bidoublets under $SU(2)_L \times SU(2)_R$
- Consistent with precision EW data
- Gauge bosons with masses accessible at LHC

Agashe, Contino, Da Rold, Pomarol